SECTION 4 - COMPARISON TO NTIA TEST RESULTS

APPROACH

General

Because the test approaches used by NTIA and ARL UT were not identical, the first step in the comparison of results was necessarily the identification of comparable subsets of data from within the two data sets. Once the comparable data was identified, an appropriate performance metric was selected for use in the comparison. Finally, adjustments were made to the data to account for the differences in desired and undesired power levels used in the tests and for the units of measure used to report these power levels. Because NTIA is not permitted to disclose the specific receiver models tested or to identify the manufacturers, comparisons according to specific models are not possible.

Identification of Comparable Data Subsets

UWB Signal Types

The NTIA test and analysis effort demonstrated that the UWB signal effects on GPS receiver performance is highly dependent on the UWB signal structure. UWB signals at the same root-mean-squared (RMS) average power level with different signal structures can have vastly different effects on GPS receiver performance. In the NTIA effort, the UWB effects were categorized as pulse-like, continuous wave (CW)-like, or noise-like.

Pulse-like effects are comparable to those observed to occur in the presence of low duty cycle (non-UWB) pulsed interference. The magnitude of such effects cannot be predicted solely on the basis of average interference power level in the receiver passband, and depends on the specific PRF, amplitude, and duration. In the case of UWB signals impinging on a GPS receiver, the apparent pulse duration and amplitude is a function of not only the UWB signal characteristics, but is also a function of the receiver impulse response. However, pulse-like effects can be described qualitatively as being much less severe than those produced by Gaussian white noise at the same RMS average power level within the receiver passband. For many of the UWB signal conditions characterized as being pulse-like, UWB signal effects on GPS receiver performance could not be observed over the range of UWB power levels available in the NTIA tests.

CW-like effects are comparable to those observed for CW interference and occur because of discrete spectral lines present in the interfering signal. The magnitude of these effects cannot be predicted solely on the basis of the average interference power level in the receiver passband, and depends on the amplitudes of the spectral lines. Furthermore, CW-like effects are time-varying in that they occur as a result of the alignment of one or more spectral lines of the interfering signal with one or more spectral lines in the received GPS signal. Because of the continually varying Doppler shift present on the GPS signal (a function of the GPS satellite velocity relative to the receiver), this alignment of spectral lines tends to be intermittent and to occur at different times for different satellites. Thus, the CW-like effects tend to be intermittent and require larger sample sizes (longer data collection times) to quantify reliably. CW-like effects can be characterized qualitatively as being substantially worse than those produced by Gaussian white noise at the same RMS average power level within the receiver passband.

Noise-like effects are comparable to those observed for Gaussian white noise interference. The magnitude of these effects can be predicted based on the RMS average interference power level in the receiver passband, or alternately on the RMS average power spectral density.

If agreement between the data sets collected by NTIA and ARL UT is to be found, the comparison must involve UWB signals of a similar type, as characterized above. Based on the factors described above, the results associated with the UWB signal conditions that produce noise-like effects were used for the comparison of the NTIA and ARL UT test results. These results would be expected to exhibit the closest agreement if the test approach differences can be properly accounted for.

In the NTIA tests, the UWB conditions that produced noise-like effects on the L_1 C/A code receiver were the 5 MHz and 20 MHz PRF, 100% duty cycle, dithered signals (both 50% absolute and 2% relative dither). The UWB conditions in the ARL UT tests that most resemble the noise-like UWB conditions in the NTIA tests are the 5 MHz and 10 MHz, 100% duty cycle signals, which were designated UWB Modes 7 and 13. ARL UT did not use a 20 MHz PRF, nor did NTIA use a 10 MHz PRF. However, because the 5 and 20 MHz PRFs produced comparable results in the NTIA tests, a 10 MHz PRF for similar waveforms would be expected to produce similar results.

Acquisition Tests Versus Tracking Tests

Both organizations performed separate tests to evaluate acquisition and tracking performance of the GPS receivers in the presence of UWB signals. For both types of tests, the two organizations used different test approaches, which would preclude the direct comparison of results even if the same GPS receivers and UWB signals were used.

For both acquisition and tracking, the NTIA tests used a GPS constellation of four GPS SVs, while the ARL UT tests used a constellation that varied between 8 and 12 SVs. In the NTIA tests, one SV was set to -130 dBm for C/A code receiver tests. The other three SVs were set 5 dB stronger. The tracking performance of the receiver was evaluated with respect to the tracking of the weakest SV. In the ARL UT tests, all SVs were set to the same power level, which varied among receivers.

In addition to the differences noted above, the test approaches used for acquisition testing differed in several other respects. The acquisition tests performed by both organizations actually measured time to reacquire SVs that were previously being tracked. However, in the NTIA tests, the GPS signal outage occurred for a single SV (the one set to the weakest power level) and was 10 seconds in duration. A 50 meter step in pseudorange was forced to occur during the outage. In the ARL UT tests, the GPS signal outage occurred for the entire constellation and was 30 seconds in duration, with no changes in simulated receiver position. Because of these differences in the acquisition test approach, the test results would be expected to differ, even if the same receivers and UWB signals were used. Furthermore, the adjustments to the data required to account for these differences to allow a comparison may not be straightforward.

Because the test approach differences are greater for the acquisition tests than for the tracking tests, the comparison of test results focused on the tracking test data.

Selection of a Performance Metric

The NTIA test and analysis report used breaklock as the primary performance metric in the tracking tests. Several other metrics were recorded, but the test results are presented in terms of the UWB power levels that cause loss of receiver lock (breaklock) on the GPS SV with the weakest power level. The ARL UT data was provided in a raw, unprocessed format from which a variety of performance metrics, including breaklock, can be derived. Therefore, the metric used for the data comparison is the UWB power level at which breaklock occurs.

Because all GPS SVs were set to the same power level, the first breaklock would not necessarily occur for the same SV in every case. Furthermore, because of the 8-hour maximum duration of the ARL UT test runs, the GPS constellation changes over the course of the test. The receiver ceases to track various satellites as they drop below the elevation mask used by the receiver. Therefore, breaklocks are evaluated by subtracting the number of SVs tracked in the baseline test (with only the desired GPS signals present) from the number of SVs tracked in a given test with UWB (or white noise) signals present. A reduction in this quantity indicates that either a breaklock occurred in the UWB-on case or the receiver failed to acquire a new satellite in the UWB-on case when that satellite was acquired in the baseline case. Because some of the GPS receivers in some of the test cases were observed to recover (resume tracking the same number of SVs as in the baseline case) after a breaklock on one SV, the point at which breaklock on multiple SVs occurred was also considered. Therefore, for the comparison of the NTIA and ARL UT data, the following three events were considered separately in the examination of the ARL UT data:

1. breaklock on one SV (total SVs tracked drops by 1 with respect to the baseline case)
2. breaklock on multiple SVs (total SVs tracked drops by more than 1 with respect to the baseline case)
3. failure to acquire a rising SV.

When extracting these events from the ARL UT data set, momentary occurrences (on the order of a few seconds) of the events listed above were ignored to account for the fact that, in multiple runs under the same conditions, the receiver may acquire a rising SV or stop tracking a setting SV at slightly different times during the simulation. The events identified for the results comparison are those that were more clearly attributable to the presence of the undesired signals. These events typically persisted for more than a minute.

Note that in the NTIA tests of the codeless tracking receiver, the breaklock metric represented the occurrence of a single cycle slip, whereas in the tests of the C/A code receiver, breaklock consisted of loss of all tracking on the SV in question. The comparison of test results was based on the C/A code tracking performance of all the receivers. Therefore, the breaklock levels determined from the ARL UT data set were compared to the C/A code receiver test results reported by NTIA.

In tests of Receivers 6 and 7, the strongest white noise and UWB power levels used in the tests were not sufficient to produce breaklocks in either of these receivers. Therefore, no comparison of white noise and UWB breaklock power levels can be made for these receivers. Other anomalous circumstances suggest that the data for Receivers 6 and 7 may not be valid, possibly due to calibration errors in the test setup used for these two receviers. For example, the information provided by ARL UT indicated that Receiver 6 was operating satisfactorily with a GPS input power weaker than -145 dBm. This represents an unreasonably weak GPS power level at which the receiver should be unable to operate. Because of the problems noted with the data for Receivers 6 and 7, this data was not considered in this analysis.

Adjustments to Data

Overview

In the comparison of the UWB power levels at which breaklock occurred in the NTIA and ARL UT tests, adjustments were required to account for three factors:

1. NTIA reported UWB power levels in terms of RMS average dBm in a 20 MHz bandwidth, but ARL UT reported UWB power levels in terms of log average dBm in a 1 MHz bandwidth.

2. NTIA included white noise at a level of -93 dBm/20 MHz in all of the tests involving UWB signals but ARL UT included no white noise in the UWB test cases (both organizations did perform tests using white noise as the only undesired signal, however).
3. NTIA and ARL UT used different GPS power levels in many cases.

UWB Power Level Reference

The different power references used in the NTIA and ARL UT test efforts would not appear to permit direct comparison. Furthermore, NTIA Report 01-383,[4] which documents the measurements of the characteristics of several types of UWB devices, shows that conversion between these metrics is highly dependent on the actual UWB signal structure. While the RMS average power measured in various bandwidths varies only as a function of the measurement bandwidth, the log average power measured in various bandwidths can vary with signal type as well as measurement bandwidth. However, the UWB device used at ARL UT appears comparable to "Device D" characterized in Reference 4. For Device D, the log average power in a 1 MHz bandwidth is approximately 2.5 dB weaker than the RMS average in the same bandwidth for the 100% burst duty cycle modes with PRFs of 1 MHz and 10 MHz. This relationship is expected to hold true for the 5 MHz case because this PRF falls between the 1 and 10 MHz cases for which the relationship is valid. Thus, the UWB power levels measured at ARL UT for the 100% duty cycle cases can be converted to RMS dBm/20 MHz by adding 15.5 dB (2.5 dB for the log to RMS conversion and 13 dB for the 1 MHz to 20 MHz bandwidth conversion).

Total Interference Power Level

The breaklock UWB power levels reported by NTIA indicate the amount of UWB power that was added to the white noise that was present in all of the tests. A direct comparison of the breaklock UWB power levels from the NTIA and ARL UT test data would only be possible if both organizations had used the same combinations of white noise and UWB signals, which was not the case. Therefore, the comparison of results is based on the total interference power. The UWB power levels reported by NTIA were added to the white noise level (-93 dBm/20 MHz) to obtain the total power. This addition was performed by converting the UWB and white noise power levels to linear terms (milliwatts/20 MHz), adding, and then converting back to logarithmic terms (dBm/20 MHz). In the ARL UT tests, the UWB power represents the total interference power because no white noise was added.

[4] William A. Kissick, *The Temporal and Spectral Characteristics of Ultrawideband Signals*, NTIA Report 01-383, Washington, DC: National Telecommunications and Information Administration, January 2001.

GPS Power

The NTIA C/A code receiver tests used a GPS power level of -130 dBm. This corresponds to the guaranteed minimum GPS power level at the output terminals of a 0 dBi receiving antenna. One SV in the constellation of four SVs was set to the stated minimum power level. The other three SVs had power levels that were 5 dB stronger. All of the breaklock data was collected with respect to the SV at the minimum power level.

The ARL UT "minimum level" tests used different GPS power levels that depended on which receiver was being tested. Receiver 1 had GPS L_1 at -129.8 dBm, which was essentially the same as in the NTIA C/A Code tests (0.2 dB stronger). Receivers 2 and 4 had GPS L_1 at -124.1 dBm, which was 5.9 dB stronger than the NTIA C/A Code tests. Receiver 3 had GPS L_1 at -136.6 dBm, which was 6.6 dB weaker than the NTIA C/A Code tests. Although different power levels were used for the different receivers, the test conditions were set up to represent the "guaranteed minimum" GPS power level condition. The differences in power level are ostensibly due to differences in gain or loss between the point in the system at which the minimum signal level is present (i.e., the output of the antenna terminals) and the actual receiver input terminals. To enable a comparison to the NTIA test results, all of the GPS and UWB power levels were referenced to the point in the system at which the GPS signal level was equal to -130 dBm. This results in the following adjustments to the breaklock UWB power levels:

- Receiver 1: subtract 0.2 dB
- Receivers 2 and 4: subtract 5.9 dB
- Receiver 3: add 6.6 dB.

OBSERVATIONS

NTIA Results

The results for L_1 C/A code receiver in Table 2-1 of NTIA Special Publication-01-45 show that white noise causes breaklock at -87 dBm/20 MHz. The 5 MHz and 20 MHz, 100% duty cycle, dithered UWB conditions (which were characterized as noise-like) cause breaklock at UWB power levels between -85.5 and -89.5 dBm/20 MHz. This corresponds to total power levels (UWB + added white noise) of between -84.8 and -87.9 dBm/20 MHz.

Example Calculation:

$$-85.5\ dBm/20\ MHz + (-93\ dBm/20\ MHz)$$
$$= 2.82 \times 10^{-9}\ mW/20\ MHz + 0.50 \times 10^{-9}\ mW/20\ MHz$$
$$= 3.32 \times 10^{-9}\ mW/20\ MHz = -84.8\ dBm/20\ MHz$$

ARL UT Results

The results for Receivers 1 through 4 with white noise and with UWB modes 7 and 13 are summarized in Table 4-1.

Table 4-1 Summary of ARL UT Test Results for Four Receivers and Three Interference Conditions

Receiver	Effect	White Noise	UWB Mode 7	UWB Mode 13
Rx 1	Loss of 1 SV	-83.8	-99.3	-99.7
	Loss of multiple SVs	-81.8	-88.3	-90.7
Rx 2	Failure to acquire	-103.2	-105.7	-103.1
	Loss of 1 SV	-82.2	-86.7	-88.1
	Loss of multiple SVs	-82.2	-84.7	-86.1
Rx 3	Loss of 1/multiple SVs	-83.9	-84.4	-85.8
Rx 4	Failure to acquire	-90.9	-90.4	n/a
	Loss of 1 SV	-85.9	-86.4	-90.8
	Loss of multiple SVs	-83.9	-86.4	-90.8

Example Calculation (Receiver 4, UWB Mode 7):

Permanent loss of SVs began to occur at approximately 13,788 seconds into the simulation, with 5 SVs lost by 14,585 seconds into the simulation. The UWB attenuator setting over this time period was 18 dB. The total signal path loss between the UWB source and Receiver 4 was 44.7 dB for an 18 dB attenuator setting (from ARL UT Laboratory Report TL-SG-01-01).

The UWB power at the spectrum analyzer input was -58.5 dBm/MHz (log average) for UWB Mode 7 (from the posted spectrum data). The signal path loss between the UWB source and the spectrum analyzer was 7.2 dB (from ARL UT Laboratory Report TL-SG-01-01). Thus, the UWB power at the UWB source output was:

-58.5 dBm/MHz + 7.2 dB = -51.3 dBm/MHz (log average).

The UWB power level at the input of Receiver 4 when the loss of SV occurred was:

-51.3 dBm/MHz (log average) - 44.7 dB (signal path loss) = -96.0 dBm/MHz (log average).

The corresponding power level expressed as RMS average in a 1 MHz bandwidth was:

-96.0 dBm/MHz (log average) +2.5 dB = -93.5 dBm/MHz (RMS).

The corresponding power level in a 20 MHz bandwidth was:

-93.5 dBm/MHz +10 Log [20 MHz/1 MHz] = -93.5 dBm/MHz + 13 dB = -80.5 dBm/20 MHz.

Thus, the UWB power was -80.5 dBm/20 MHz RMS when the loss of one/multiple SVs occurred. The GPS power level at the same point in the system was -124.1 dBm. At the point in the system where the GPS power level was -130 dBm, the UWB power was:

-80.5 dBm/20 MHz - [-124.1 dBm - (-130 dBm)] = -80.5 dBm/20 MHz - 5.9 dB = -86.4 dBm/20 MHz, as shown in Table 4-1 above.

Comparison of Results

Receiver 1

The white noise, 1 SV breaklock level for Receiver 1 was 1 dB stronger than the strongest breaklock level measured for noise-like signals in the NTIA C/A code receiver tests. The multiple-SV breaklock level was 3 dB stronger than the strongest breaklock level in the NTIA results. This suggests that Receiver 1 may be less susceptible to white noise interference than the receiver that was tested by NTIA, although differences in the test setups and test methods could account for the differences in the results.

The UWB, 1 SV breaklock levels for Receiver 1 were more than 10 dB weaker than the weakest breaklock level measured for noise-like signals in the NTIA C/A code receiver tests. The multiple-SV breaklock levels were between 0.4 and 2.8 dB weaker than the weakest breaklock level in the NTIA results. This suggests that Receiver 1 may be more susceptible to UWB interference than the receiver that was tested by NTIA. Although differences in the test setups and test methods could account for some of the differences in the results, these differences are not consistent with those noted for white noise signals. Therefore, issues regarding test setup and methods are not believed to account for all of the differences noted.

Within the ARL UT data set, the results for the UWB signals differed from the corresponding white noise results by between 6.5 and 15.9 dB. The UWB power levels required to produce a breaklock (on one or multiple SVs) were substantially weaker than the white noise power levels required to produce the same type of breaklock. By comparison, the NTIA results for noise-like UWB signals varied over a 3.1 dB range that encompassed the white noise results. This suggests that Receiver 1 is more susceptible to UWB interference than to white noise interference and that UWB Modes 7 and 13 are not properly categorized as noise-like with regard to their effects on Receiver 1. The effects of these modes are substantially worse than those produced by the same amount of white noise, and are indicative of CW-like effects. This observation is based on comparison of results within the ARL UT data set itself; thus, test setup differences between NTIA and ARL UT are not an issue.

Receiver 2

The white noise, 1 SV and multiple-SV breaklock levels for Receiver 2 were 2.6 dB stronger than the strongest breaklock level measured for noise-like signals in the NTIA C/A code receiver tests. This suggests that Receiver 2 may be less susceptible to white noise interference than the receiver that was tested by NTIA, although differences in the test setups and test methods could account for the differences in the results.

All of the 1 SV and multiple-SV breaklock levels for the UWB signals fell within 0.2 dB of the range of breaklock levels measured for noise-like signals in the NTIA C/A code receiver tests.

The differences between the UWB and white noise results for Receiver 2 were slightly less than 6 dB, and thus were much less than those observed for Receiver 1. Therefore, a noise-like characterization for UWB Modes 7 and 13 is more reasonable with regard to the effects on Receiver 2 than for Receiver 1.

The failure-to-acquire power levels shown in Table 4-1 are not considered to be indicative of a breaklock phenomenon, but rather are indicative of effects on acquisition performance. At the power levels shown, Receiver 2 was unable to acquire new SVs rising into the constellation. This condition is different than either of the reacquisition conditions tested by ARL UT and NTIA. The failure-to-acquire levels are observed to be much weaker than those that produce a breaklock.

Receiver 3

The white noise breaklock level was 0.9 dB stronger than the strongest breaklock level measured for noise-like signals in the NTIA C/A code receiver tests. The UWB breaklock results fell within 0.4 dB of the range of breaklock levels measured for noise-like signals in the NTIA C/A code receiver tests.

The white noise and UWB results for Receiver 3 fell within a 1.9 dB range. Therefore, the UWB results for Receiver 3 are properly characterized as noise-like.

Receiver 4

The white noise, 1 SV breaklock levels for Receiver 4 fell within the range of breaklock levels measured for noise-like signals in the NTIA C/A code receiver tests. The multiple-SV breaklock level was 0.9 dB stronger than the strongest breaklock level in the NTIA results.

The 1 SV and multiple-SV breaklock levels for the UWB Mode 7 signals fell within the range of breaklock levels measured for noise-like signals in the NTIA C/A code receiver tests. The breaklock levels for UWB Mode 13 were 2.9 dB weaker than the weakest breaklock levels in the NTIA results.

The differences between the UWB and white noise results for Receiver 4 were much less than those observed for Receiver 1. Therefore, a noise-like characterization for UWB Modes 7 and 13 is more reasonable with regard to the effects on Receiver 4 than for Receiver 1.

The failure-to-acquire power levels shown in Table 1 are not considered to be indicative of a breaklock phenomenon, but rather are indicative of effects on acquisition performance. At the power levels shown, Receiver 4 was unable to acquire new SVs rising into the constellation. This condition is different than either of the reacquisition conditions tested by ARL UT and NTIA.

SUMMARY OF COMPARISON

The results of separate tests performed by ARL UT and NTIA to evaluate the performance of GPS receivers in the presence of UWB emissions were examined and compared. The results for Receivers 1 through 4 in the ARL UT tests and the results for the C/A code receiver in the NTIA tests were considered in the comparison. The RMS interference power level that produced a GPS receiver breaklock was selected as the performance metric to be used as the basis for the comparison. The results for the 100% duty cycle, dithered, 5 MHz and 10 MHz PRF signals (UWB Modes 7 and 13) in the ARL UT tests were compared to the results for the 100% duty cycle, dithered, 5 MHz and 20 MHz PRF signals in the NTIA tests. The white noise test results from both programs were also considered in the comparison. Adjustments were made in the data to account for differences in the test methods.

The UWB signal conditions, considered in this comparison, produced noise-like effects on Receivers 2, 3, and 4 in the ARL UT tests. The white noise and UWB test results for these receivers were reasonably consistent with the NTIA results.

The same UWB signal conditions that produced noise-like effects on Receivers 2, 3, and 4 produced effects on Receiver 1 that were substantially worse than those produced by white noise on the same receiver in the ARL UT tests. The ARL UT test results for Receiver 1 were not in agreement with the NTIA results for noise-like conditions. The results for Receiver 1 are suggestive of CW-like effects.

SECTION 5 - COMPARISON OF NOISE-LIKE AND CW-LIKE EFFECTS

OVERVIEW

The analysis presented in Section 4 found that the UWB interference effects on Receiver 1 deviated substantially from a noise-like characteristic. This finding was based on the comparison of breaklock power levels for UWB and white noise interference. This section provides a more detailed examination and comparison of the white noise and UWB interference effects on Receiver 1 tracking performance that includes several other performance metrics.

This comparison considered all three of the 100% duty cycle UWB signal types tested at ARL UT. The UWB signals are designated Modes 1, 7, and 13, and have PRFs of 1, 5, and 10 MHz, respectively. Table 5-1 lists the RMS average white noise UWB power levels as a function of test time (i.e., seconds after the start of the test). Plots to be presented later in this section present values of various performance metrics as a function of test time. Thus, Table 5-1 provides a useful reference for finding the test conditions that correspond to various phenomena observed in the plots.

Table 5-1. Interference Power Levels as a Function of Test Time

Continuous White Noise		PRF = 1 MHz UWB Mode 1		PRF = 5 MHz UWB Mode 7		PRF = 10 MHz UWB Mode 13	
Test Time (seconds)	Power (dBm/ 20 MHz)	Test Time (seconds)	Power (dBm/ 20 MHz)	Test Time (seconds)	Power (dBm/ 20 MHz)	Test Time (seconds)	Power (dBm/ 20 MHz)
377	-125.6	377	-135.8	377	-128.1	377	-125.5
1682	-108.6	1640	-118.8	1689	-111.1	1751	-108.5
3005	-105.6	2901	-115.8	3013	-108.1	3141	-105.5
4329	-102.6	4166	-112.8	4338	-105.1	4533	-102.5
5657	-99.6	5434	-109.8	5665	-102.1	5927	-99.5
6988	-96.6	6706	-106.8	6996	-99.1	7324	-96.5
8322	-93.6	7980	-103.8	8330	-96.1	8724	-93.5
9659	-90.6	9256	-100.8	9668	-93.1	10127	-90.5
11000	-87.6	10536	-97.8	11009	-90.1	11532	-87.5
12344	-85.6	11818	-95.8	12354	-88.1	12939	-85.5
13691	-83.6	13103	-93.8	13701	-86.1	14349	-83.5
15042	-81.6	14391	-91.8	15051	-84.1		
		15681	-89.8	16405	-82.1		
		16973	-87.8	17762	-80.1		
		18269	-85.8	19121	-78.1		
		19566	-83.8				
		20866	-81.8				
		22169	-79.8				
		23477	-77.8				
		24786	-75.8				

RECEIVER 1 PERFORMANCE METRICS

General

A comparison of the white noise and UWB test results for Receiver 1 was made for three selected performance metrics. The selected metrics were C/N_0, code-minus-carrier and detected cycle slips.

C/N_0

The C/N_0 metric is a raw quantity that was provided by Receiver 1. It is the receiver's estimate of the carrier-to-noise-density ratio. This quantity is provided in dB-Hz.

Code-Minus-Carrier

Code-minus-carrier is a derived quantity. It is the difference between the code and carrier pseudorange values. The pseudorange values provided by Receiver 1 are the code pseudoranges. These values are provided in meters. The carrier phase values provided by Receiver 1 are the carrier pseudoranges. The units for carrier phase are carrier cycles. The carrier phase values were multiplied by the wavelength of the GPS L_1 signal to convert them to meters, then subtracted from the corresponding pseudorange values for each epoch to obtain the code-minus-carrier metric.

Detected Cycle Slips

The detected cycle slips metric is derived from the raw lock time values provided by Receiver 1 for each SV. The lock time values for each SV indicate the cumulative time, in seconds, for which the receiver has been tracking that SV without cycle slips. Thus, the lock time value is reset to zero for a particular SV each time the receiver detects a cycle slip in the tracking of that SV. Because lock time is reported once per second with a resolution of 625 ms, the reported lock times immediately after a cycle slip are not exactly zero, but a fractional value less than one.

RECEIVER 1 TEST RESULTS

Baseline

Figure 5-1 presents the C/N_0 data for SV 7 obtained from the baseline tests of Receiver 1. SV 7 was selected for this presentation because it was visible for the entire test. Results for other SVs were similar over the time intervals in which they were visible. This similarity held true for the other metrics considered in this analysis, except where otherwise noted. Therefore, the results for SV 7 will be presented as being representative unless important differences are observed in the results for other SVs. The C/N_0 results in Figure 5-1 vary between 34 and 37 dB-Hz, with the smaller values occurring near the beginning and end of the test and the larger values occurring near the middle of the test. This trend generally follows the variations of the elevation angle of SV 7 over the course of the test. Note that all figures are presented at the end of this section.

Figure 5-2 presents the code-minus-carrier results. The average level appears to be relatively flat with a noticeable increase near the end of the test. The amount of noise appears to be of relatively constant amplitude, with the exception of a noticeable spike, or perturbation, at a test time of 27,410 seconds.

The results for cycle slips are presented in Figure 5-3. A single cluster of cycle slips is observed to occur near the end of the test at the same time as the observed perturbation in the code-minus-carrier results.

White Noise

Figure 5-4 presents the C/N_0 data for SV 7 obtained from the white noise tests of Receiver 1. Unlike the corresponding baseline plot in Figure 5-1, several gaps in the data are observed in Figure 5-4 and in all subsequent figures depicting receiver performance in the presence of interference. These gaps are the time intervals for each interference attenuator setting during which data logging was suspended. Note that the attenuator settings were changed approximately 10 seconds after each gap.

A reduction in C/N_0 is first observed to occur during the data collection interval beginning at a test time of 6988 seconds. The C/N_0 values continue to trend downward, with obvious steps coinciding with the increases in interference power level.

Figure 5-5 presents the code-minus-carrier data for SV 7. Effects on this metric become noticeable at a later point in the test than the effects on C/N_0. However, once the effects become noticeable, they continue to become more pronounced as the test time (and the interference power level) increases, until the receiver loses lock on SV 7.

Figure 5-6 presents the cycle slips results for SV 7. A few clusters of cycle slips are detected during the interval beginning at a test time of 11,000 seconds. The frequency of cycle slips steadily increases as a function of interference power level, although the individual spikes have been run together in this plot. Figure 5-7 provides a more detailed view of the cycle slips results over the interval from 10,800 to 16,800 seconds. The increase in the number of detected cycle slips as a function of interference power level is more discernable in this plot.

For all three performance metrics examined, the noise effects are characterized by a steady increase in the amount of degradation as the interference power level increases.

UWB Signals

Figure 5-8 presents the C/N_0 results for SV 7 from the tests of Receiver 1 in the presence of UWB Mode 1 signals. Unlike the corresponding white noise curve in Figure 5-4, the C/N_0 values do not degrade steadily as a function of test time (i.e., as a function of interference power level). The first obvious sign of degradation is a dip centered at a test time of approximately 9400 seconds. A much larger dip occurs at approximately 13,900 seconds. Between these two dips, the performance remains relatively unchanged over two increases in interference power level. This phenomenon is very different from the effects observed in the white noise tests. A more steady degradation over a slightly longer period of time is observed to occur near the end of the test, prior to loss of lock. Even in this case, the degradation steps corresponding to the interference power level steps are not easily discerned.

Figure 5-9 presents the code-minus-carrier results for SV 7. The first clearly observed perturbation occurs at a test time of approximately 13,900 seconds, corresponding the second C/N_0 dip observed in Figure 5-8. A comparison of Figure 5-9 with the corresponding plot of white noise results in Figure 5-5 reveals deviations from noise-like effects similar to those observed for the C/N_0 metric.

Figure 5-10 presents the cycle slips results for SV 7. These results are also observed to be markedly different from the white noise effects presented in Figures 5-6 and 5-7. The first cluster of cycle slips occurs near a test time of 13,900 seconds, coinciding with the C/N_0 and code-minus-carrier effects.

Figures 5-11, 5-12, and 5-13 present the C/N_0, code-minus-carrier, and cycle slips results for SV 7 in the tests of Receiver 1 with UWB Mode 7. Figures 5-14 through 5-16 present the corresponding results for UWB Mode 13. These results are all consistent with, although more severe than, the results observed for UWB Mode 1. The increased severity of the effects is attributed to the higher PRFs for Modes 7 and 13. These results bear little resemblance to the white noise effects presented in Figures 5-4 through 5-7. Note that in the tests with the various UWB modes, the interference power level increases did not occur at exactly the same time. In fact, the relationship between interference power level and test time varies by more than 1000 seconds in some cases (recall that each power level is maintained for a 1200 second interval). However, the UWB interference effects in all cases have the tendency to occur at approximately the same test times. In addition to the two times noted for the case of UWB Mode 1, a degradation is also discernable near a test time of 6500 seconds for UWB Modes 7 and 13.

This observed time dependency of the UWB effects on GPS receiver performance is characteristic of CW-like interference. CW interference becomes most severe when the CW spectral line(s) become aligned with a code line in the desired GPS signal. The position of the GPS code lines are a function of the GPS signal coding and the GPS carrier frequency, including the Doppler shift of the GPS signal arriving at the GPS receiver. The position of the spectral lines in an interfering UWB signal is a function of the PRF and coding technique. For the UWB signals used in the ARL UT tests, the coding scheme reduced the amplitude of the PRF-induced spectral lines relative to those that would be produced by an unmodulated UWB pulse train. However, this coding scheme did produce a large number of weaker spectral lines that were spaced in frequency by PRF/1024.

Because the same basic GPS scenario was used for all the ARL UT conducted signal tests, the Doppler shift of the signal from each SV as a function of test time was the same in every test. Because all of the UWB PRFs were harmonically related, the lower PRF modes have spectral lines in the same locations as the higher PRF modes, plus additional lines in between. For example, Mode 7 (5 MHz) has twice as many spectral lines as Mode 13 (10 MHz), and half of them occur at the same frequencies as for Mode 13. The other half occur exactly halfway between the Mode 13 lines. Therefore, alignment of certain UWB and GPS spectral lines would be expected to occur at approximately the same time in the GPS simulation.

While the CW-like effects on the performance with respect to a particular SV would tend to occur at the same test time over multiple trials, the effects on different SVs would be expected to occur at different test times because of the difference in Doppler shift values. Figures 5-17, 5-18, and 5-19 present the C/N_0 results for SV 4 in the tests of Receiver 1 with UWB Modes 1, 7, and 13, respectively. In these figures, the UWB effects tend to occur at test times of 10,600, 13,200, 15,000, 16,600, and 20,400 seconds. These are different than the times associated with the effects on SV 7. This observation is consistent with a CW-like characterization for the UWB effects on Receiver 1.

TEST RESULTS FOR OTHER RECEIVERS

The UWB effects on the other receivers in the ARL UT test program were observed to be more consistent with a noise-like characterization. Figures 5-20, 5-21, and 5-22 present the C/N_0 results for SV 7 for the UWB Mode 7 tests of Receivers 2, 3, and 4, respectively. The progressive degradation of this performance metric as a function of UWB power level is evident in all three plots.

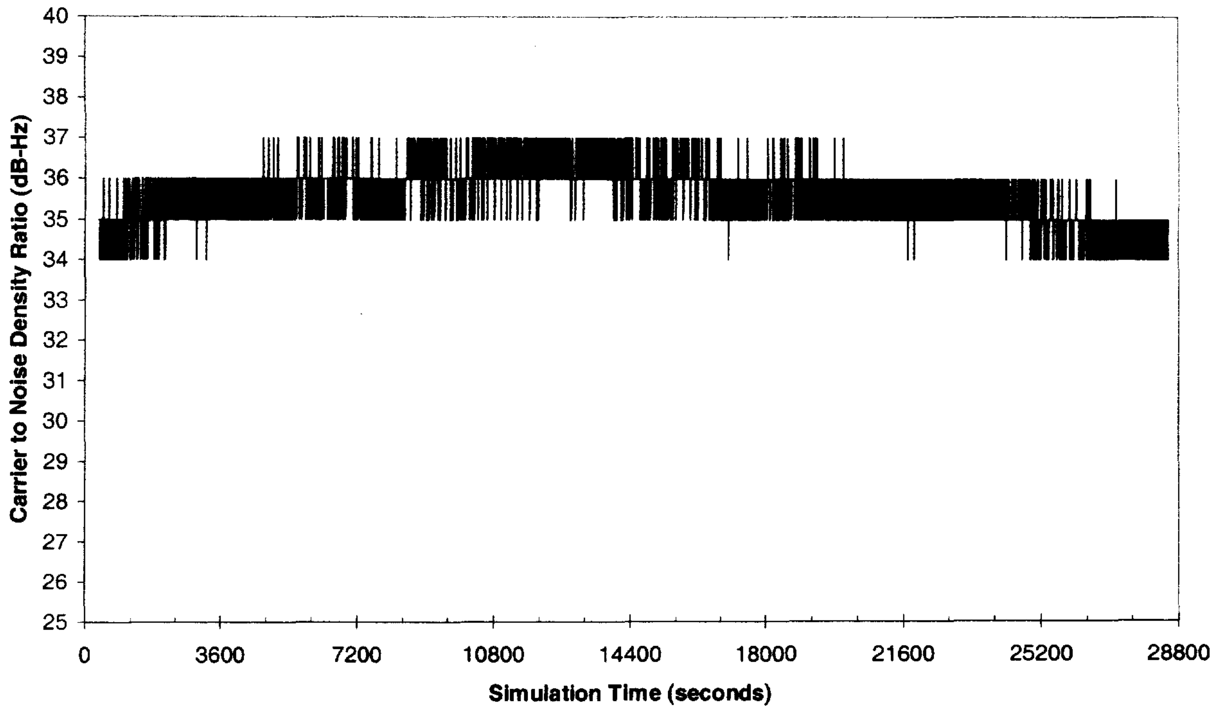

Figure 5-1. Receiver 1 SV 7 C/N$_0$, Baseline

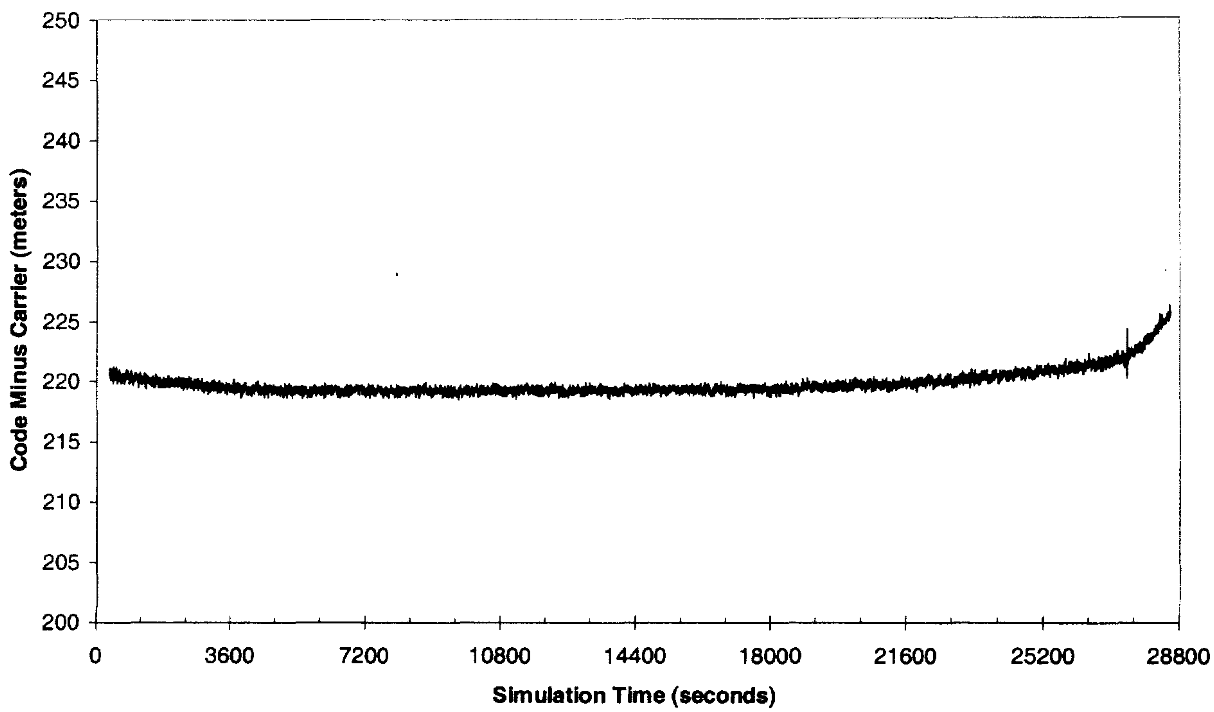

Figure 5-2. Receiver 1 SV 7 Code Minus Carrier, Baseline

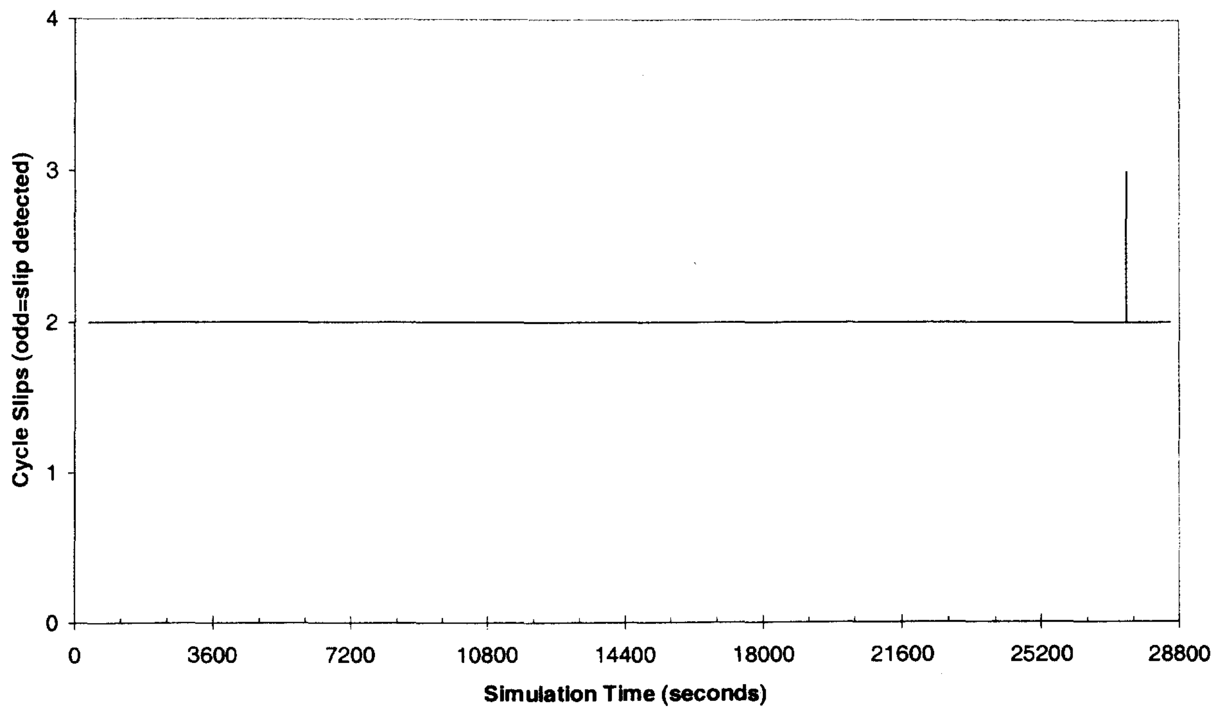

Figure 5-3. Receiver 1 SV 7 Cycle Slips, Baseline

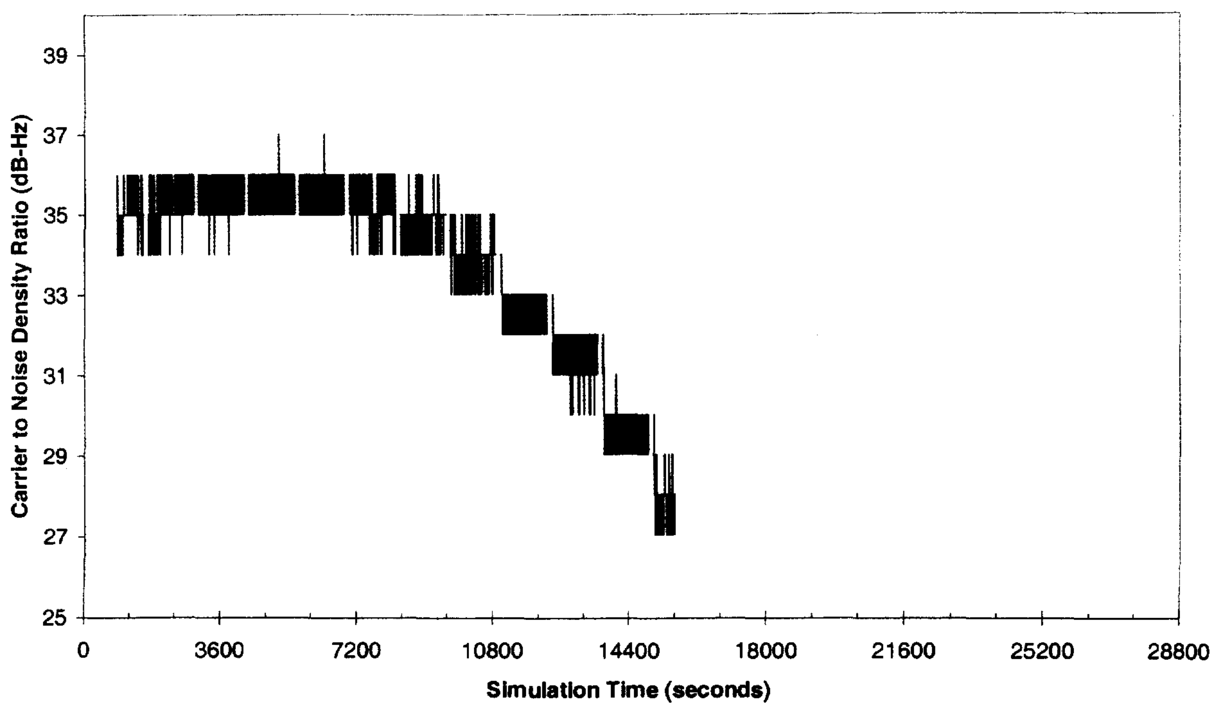

Figure 5-4. Receiver 1 SV 7 C/N$_0$, White Noise

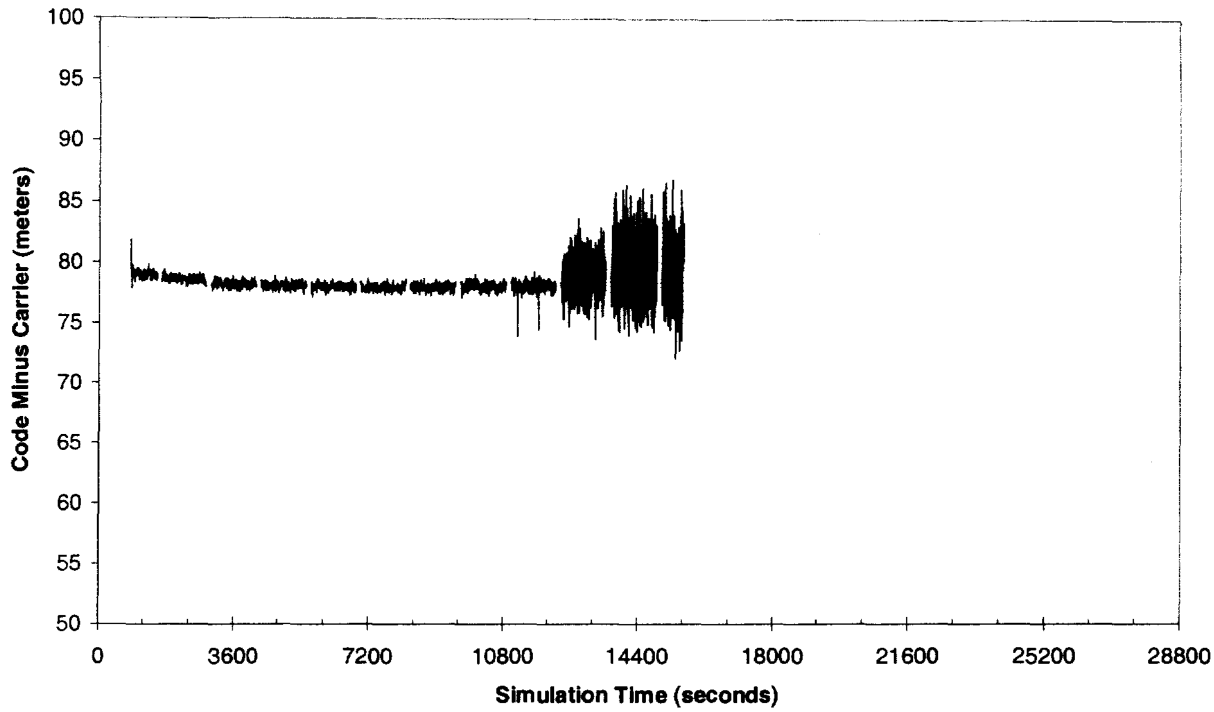

Figure 5-5. Receiver 1 SV 7 Code Minus Carrier, White Noise

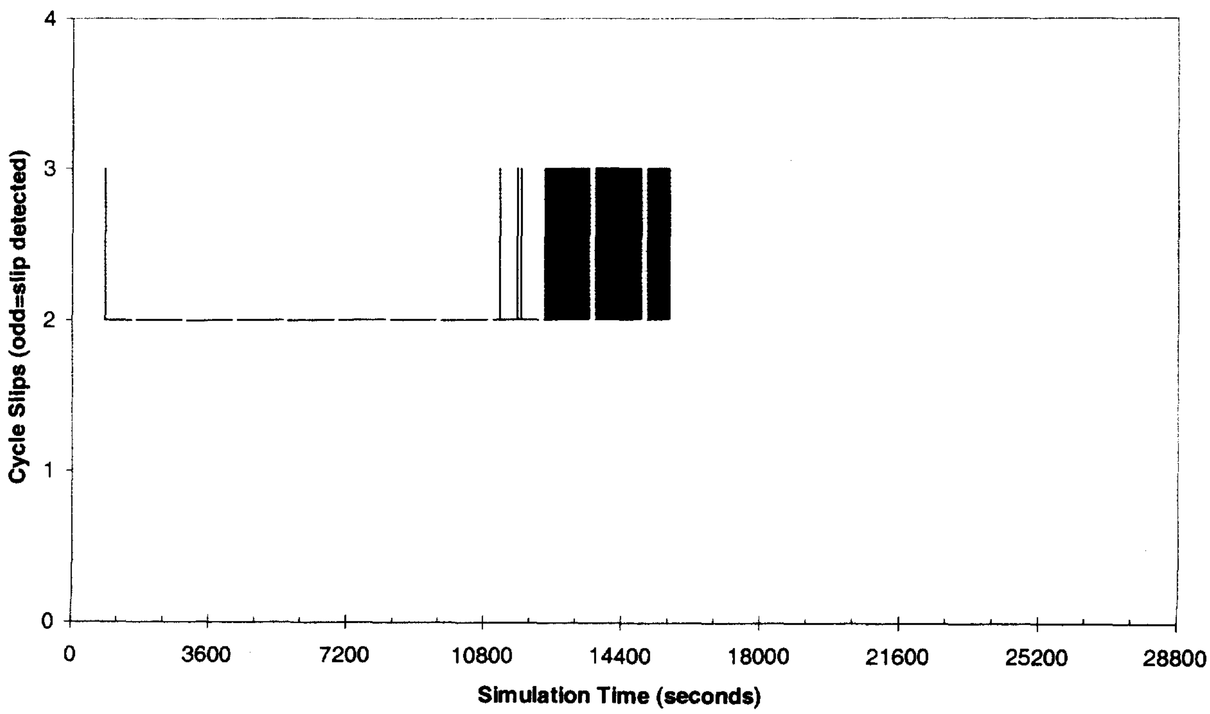

Figure 5-6. Receiver 1 SV 7 Cycle Slips, White Noise

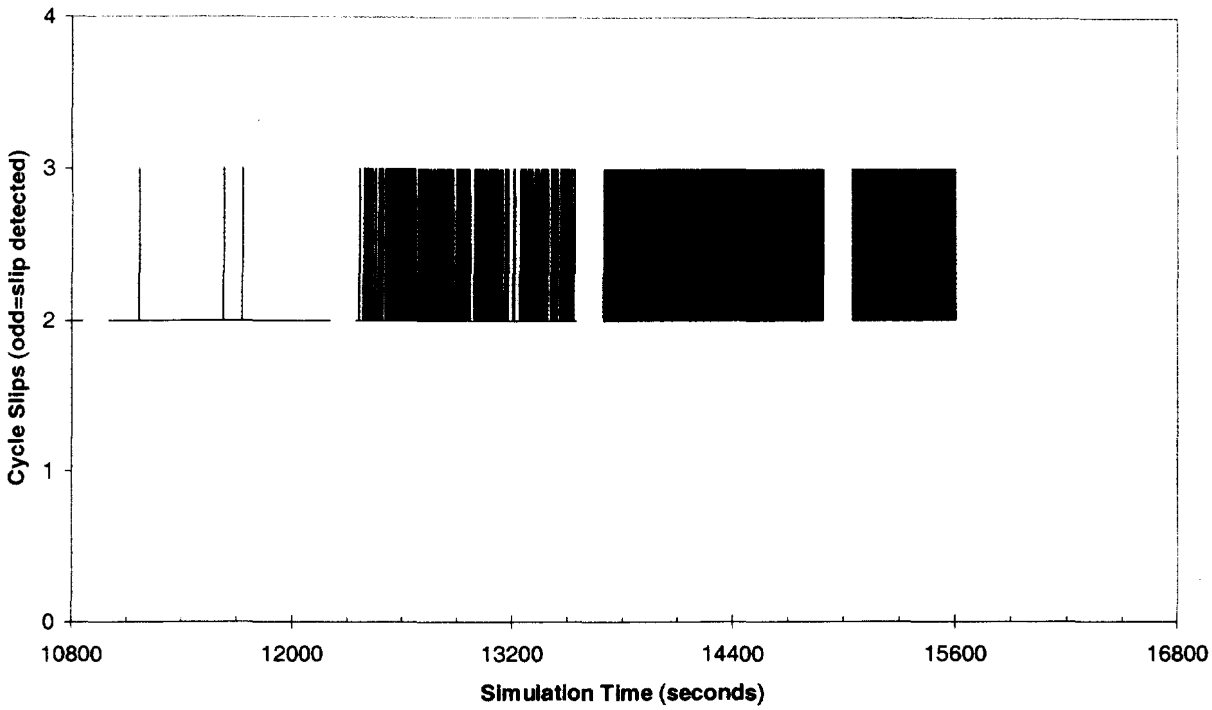

Figure 5-7. Receiver 1 SV 7 Cycle Slips (Detail View), White Noise

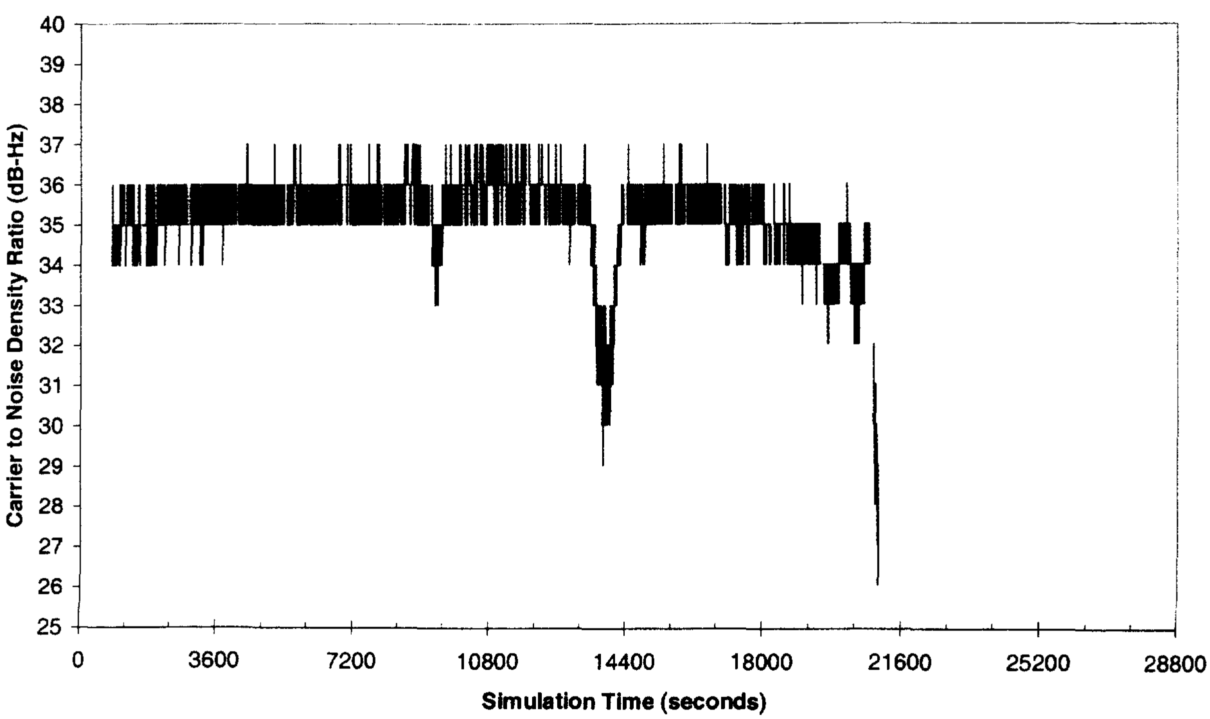

Figure 5-8. Receiver 1 SV 7 C/N$_0$, UWB Mode 1

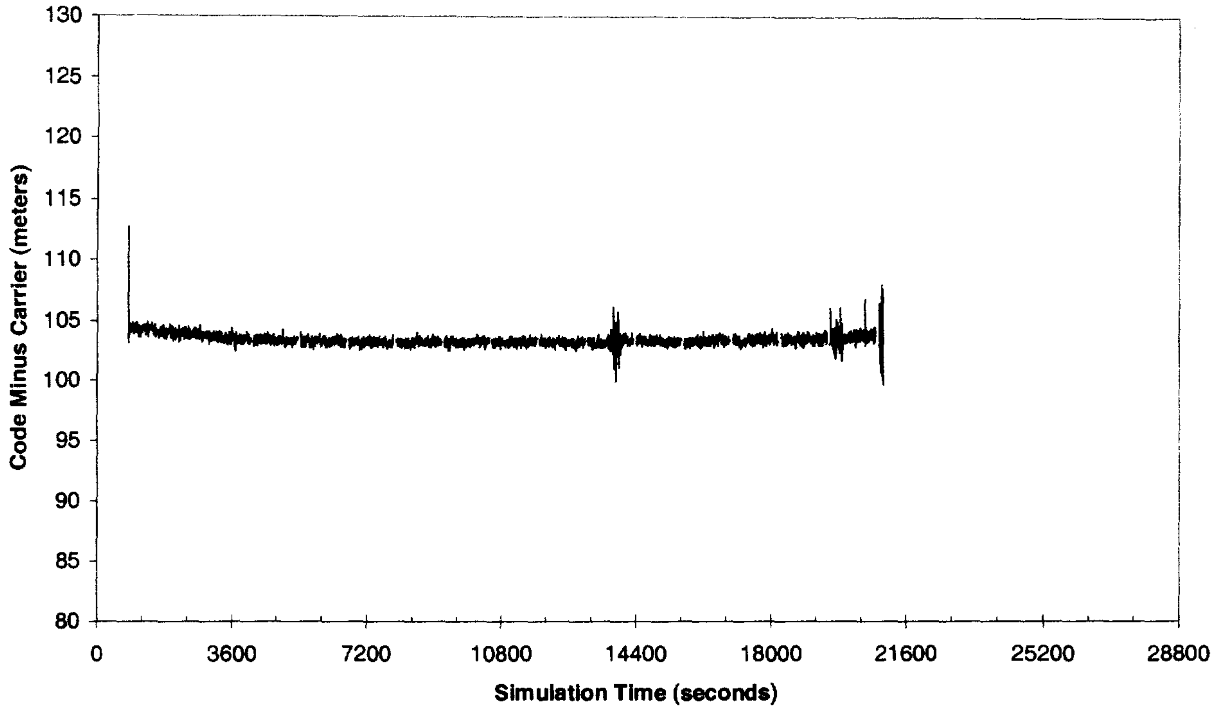

Figure 5-9. Receiver 1 SV 7 Code Minus Carrier, UWB Mode 1

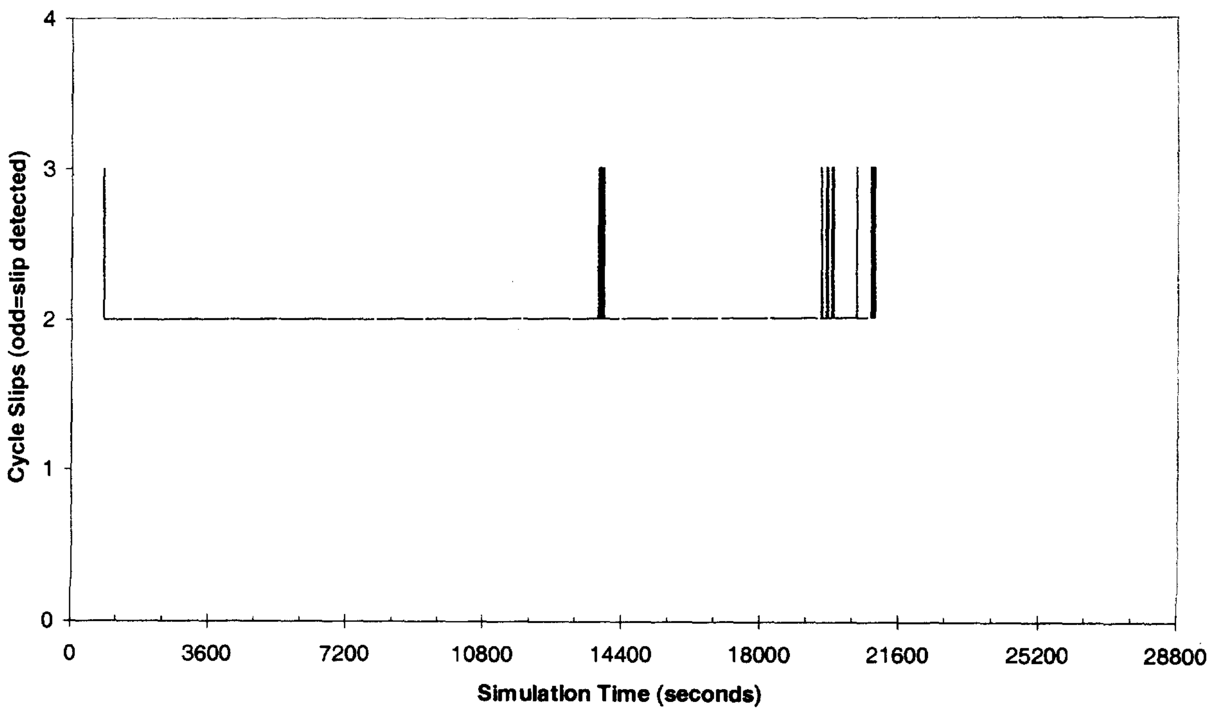

Figure 5-10. Receiver 1 SV 7 Cycle Slips, UWB Mode 1

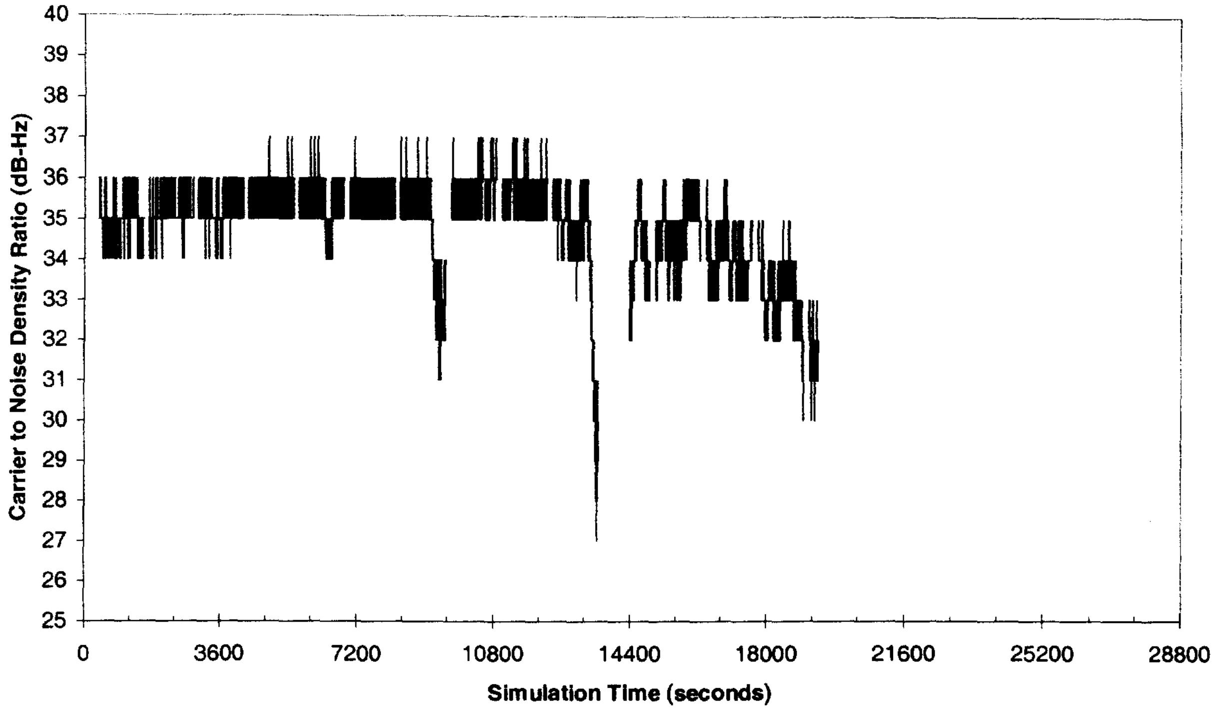

Figure 5-11. Receiver 1 SV 7 C/N$_0$, UWB Mode 7

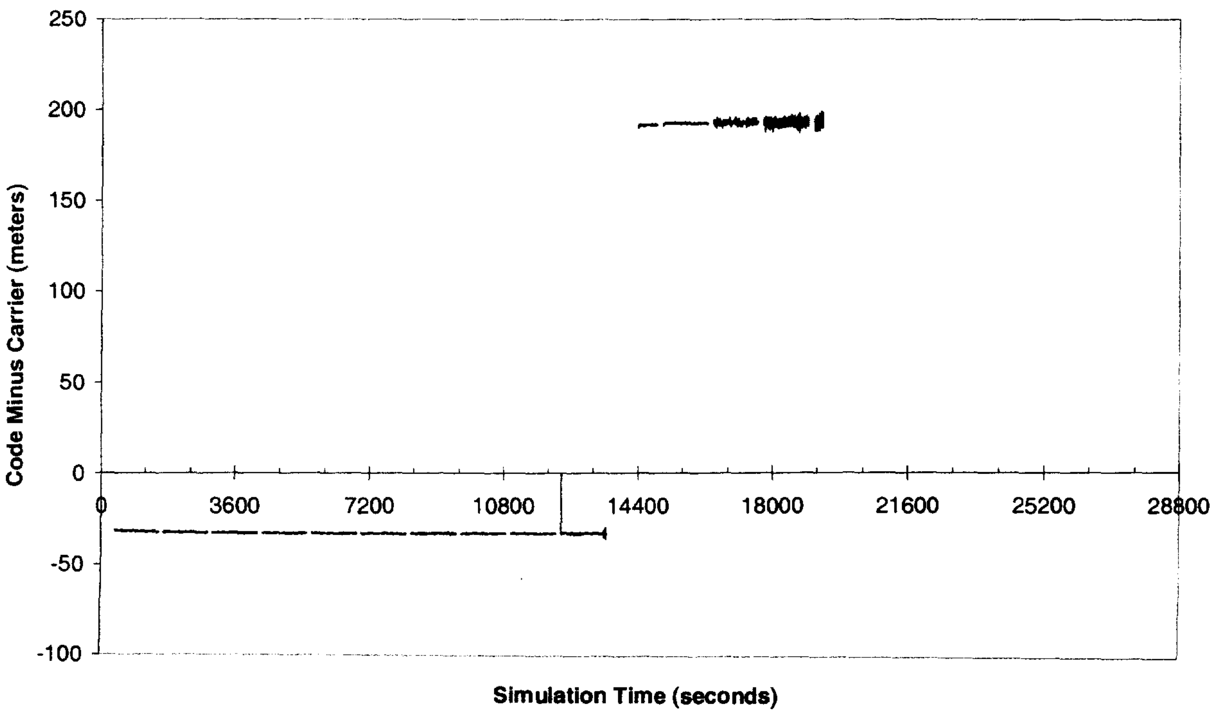

Figure 5-12. Receiver 1 SV 7 Code Minus Carrier, UWB Mode 7

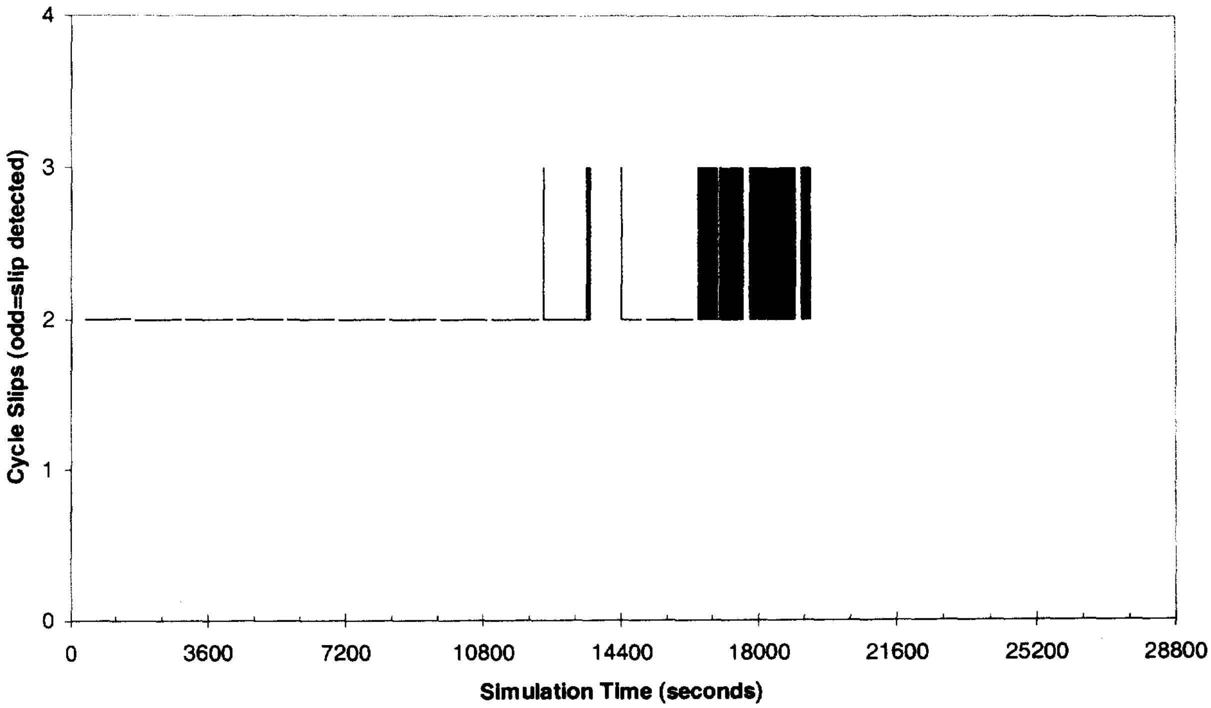

Figure 5-13. Receiver 1 SV 7 Cycle Slips, UWB Mode 7

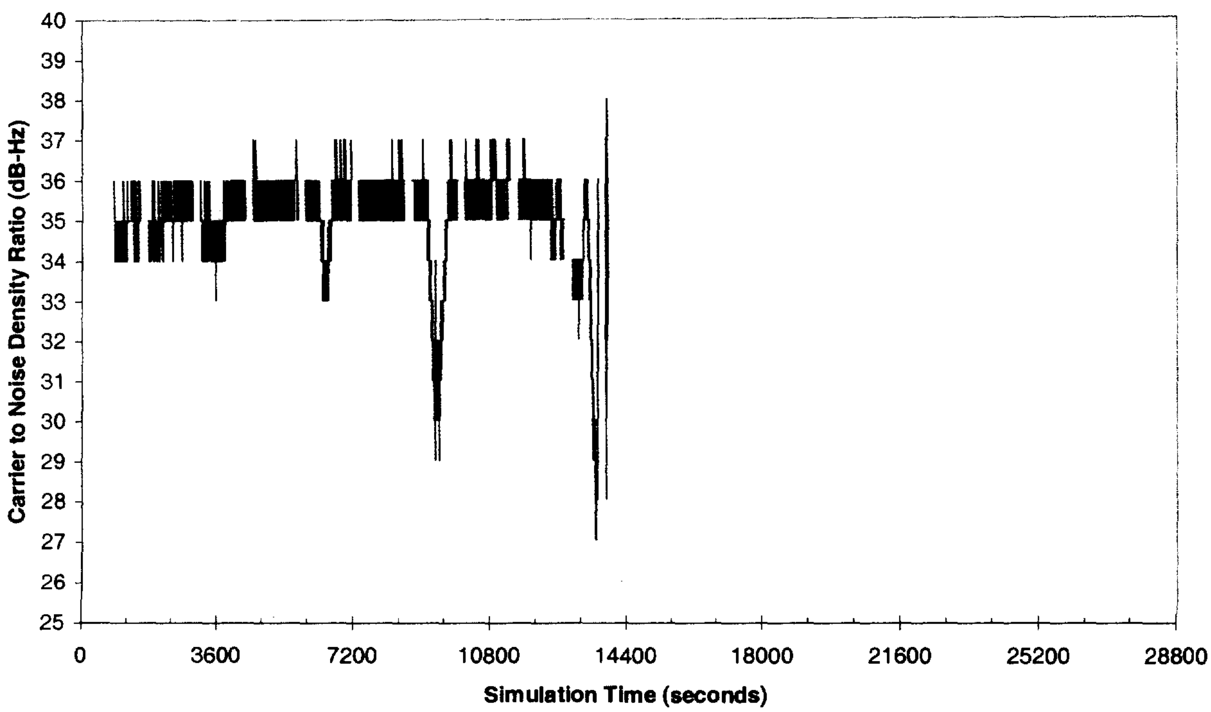

Figure 5-14. Receiver 1 SV 7 C/N_0, UWB Mode 13

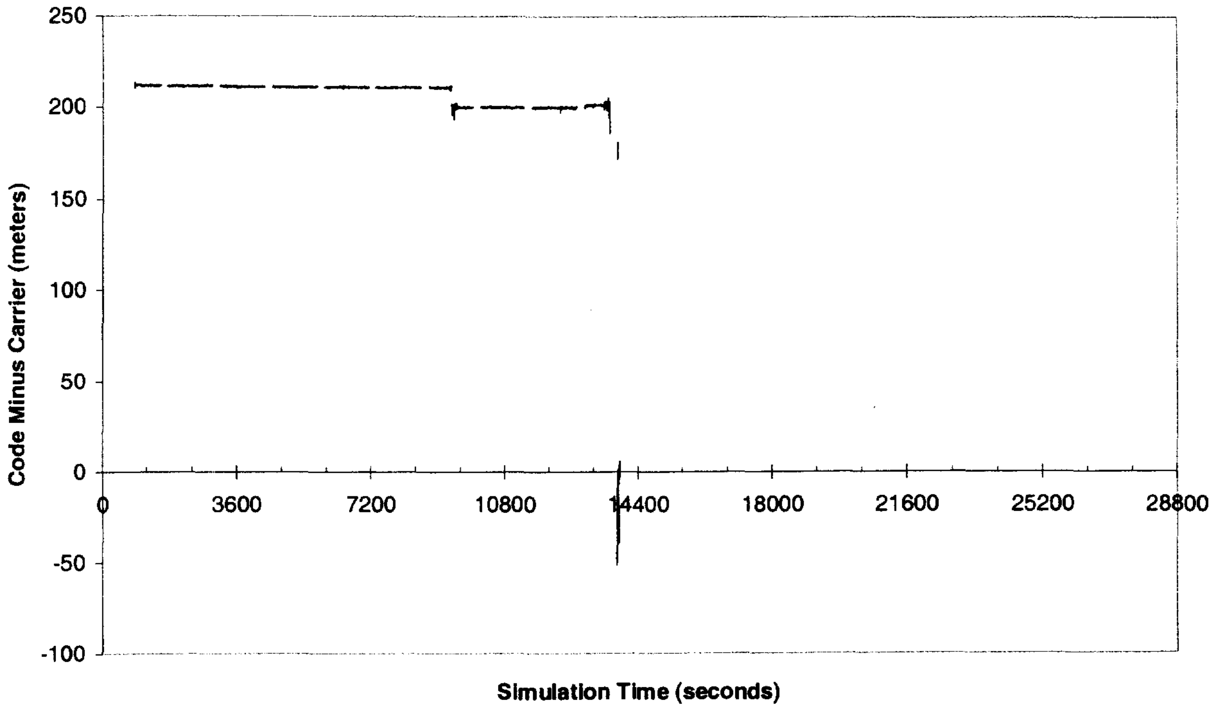

Figure 5-15. Receiver 1 SV 7 Code Minus Carrier, UWB Mode 13

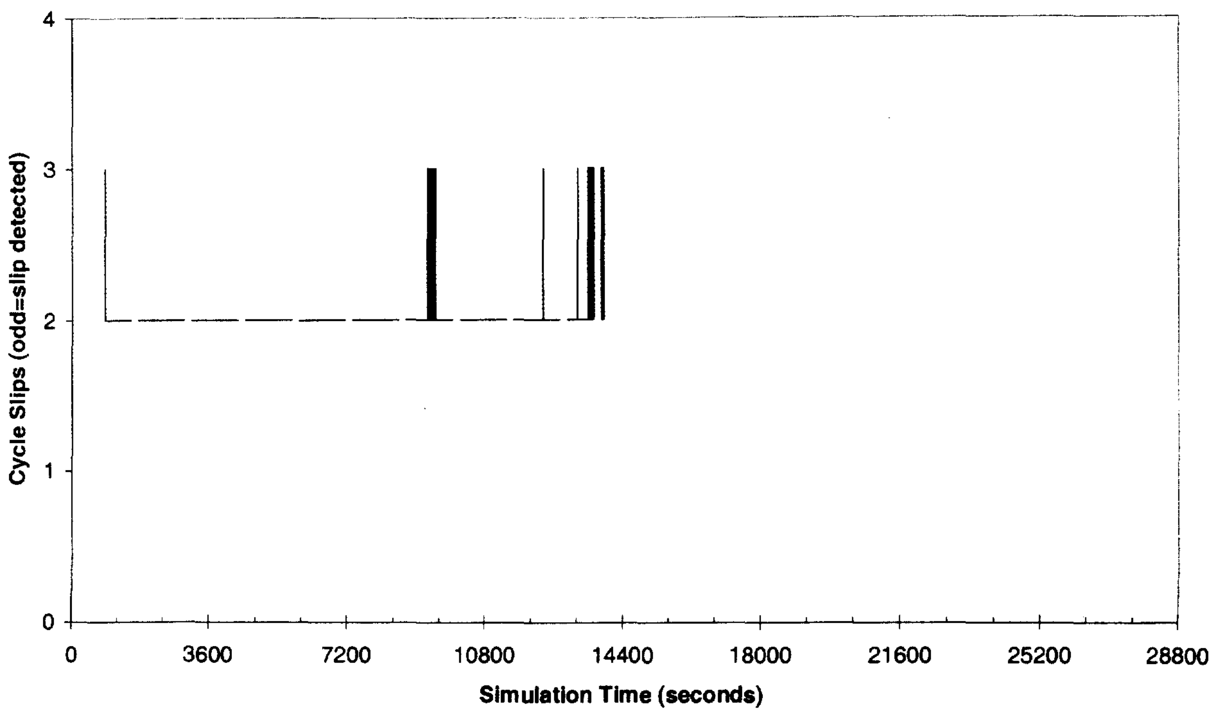

Figure 5-16. Receiver 1 SV 7 Cycle Slips, UWB Mode 13

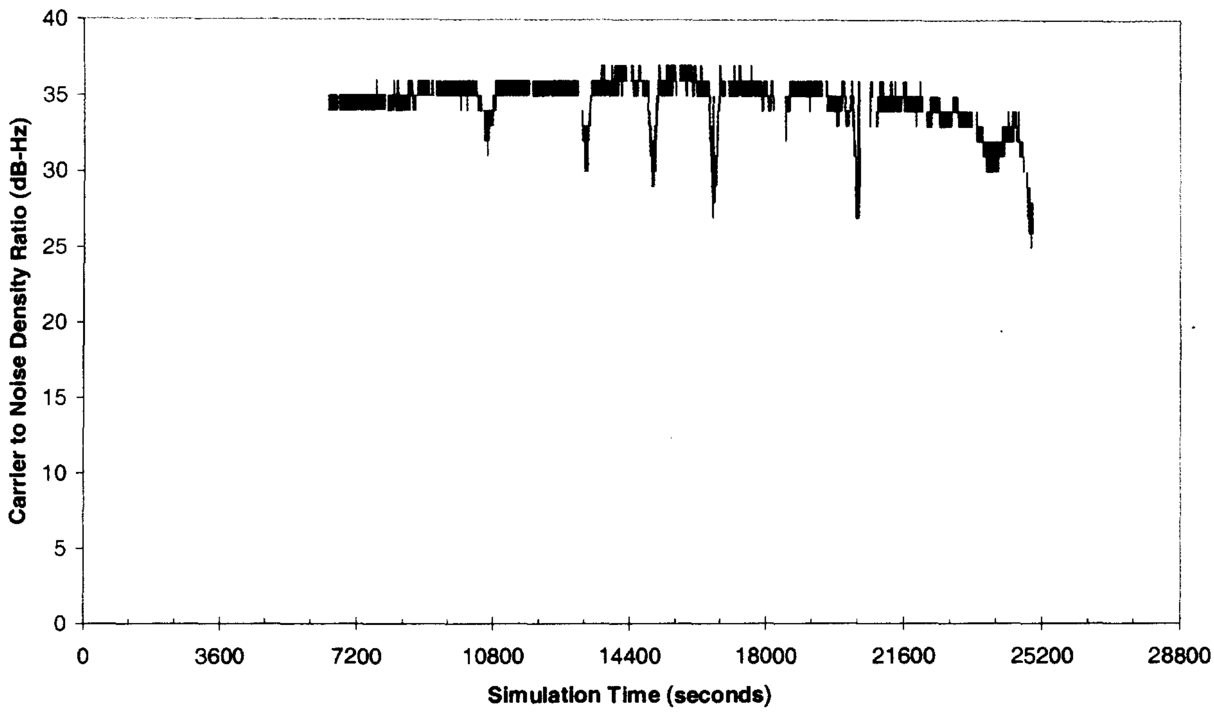

Figure 5-17. Receiver 1 SV 4 C/N$_0$, UWB Mode 1

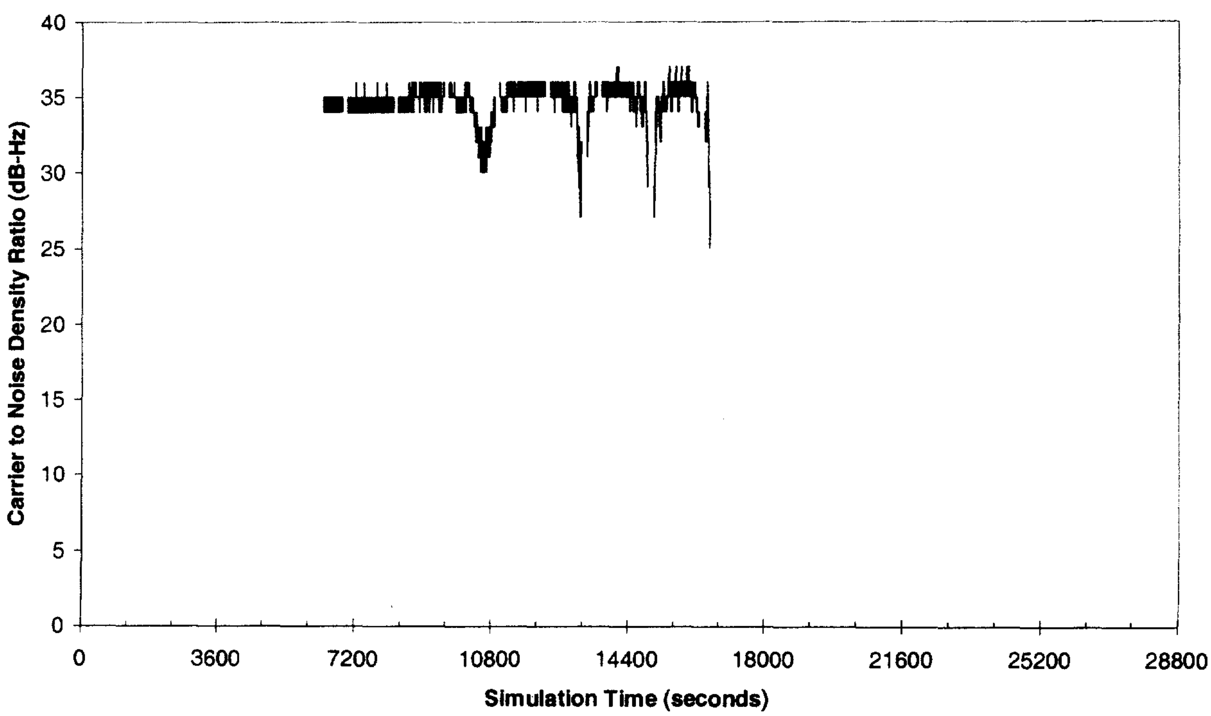

Figure 5-18. Receiver 1 SV 4 C/N$_0$, UWB Mode 7

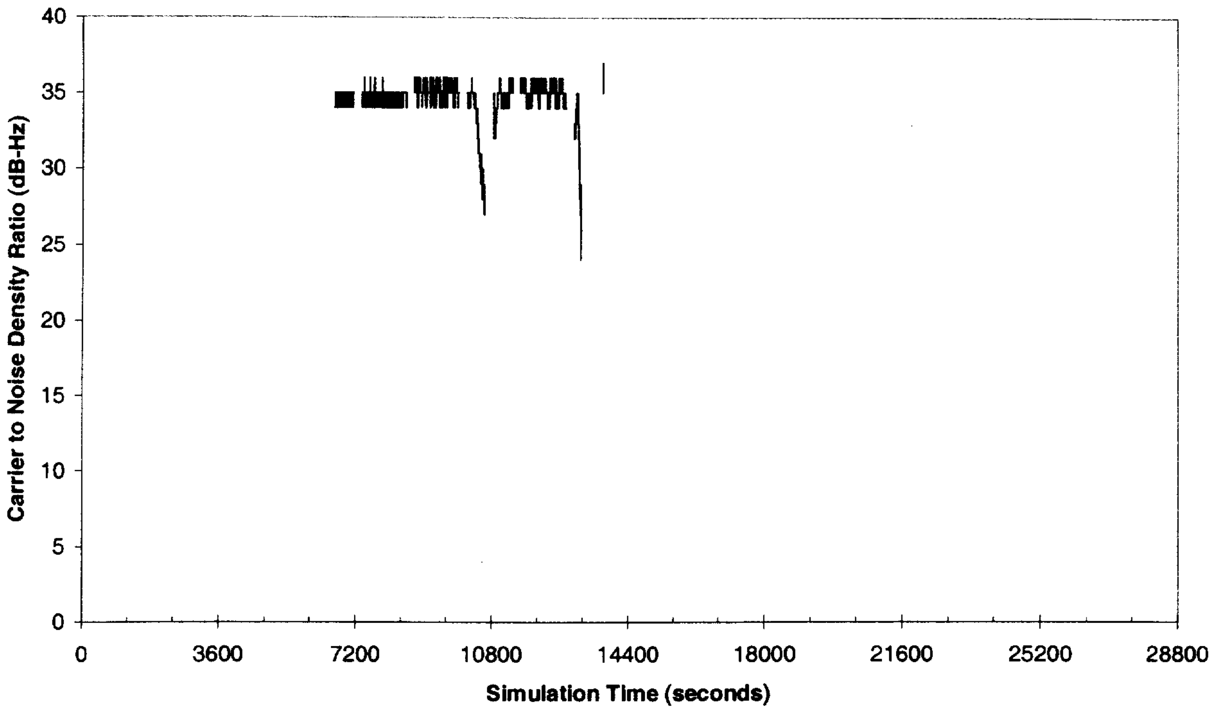

Figure 5-19. Receiver 1 SV 4 C/N$_0$, UWB Mode 13

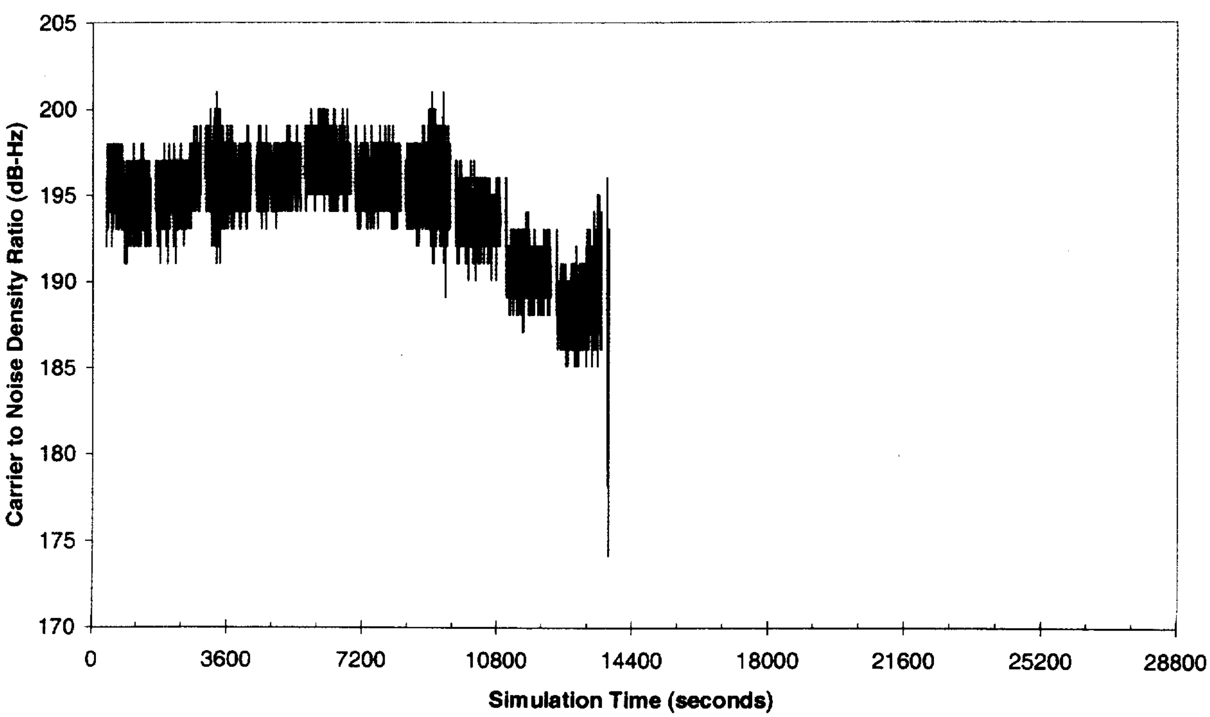

Figure 5-20. Receiver 2 SV 7 C/N$_0$, UWB Mode 7

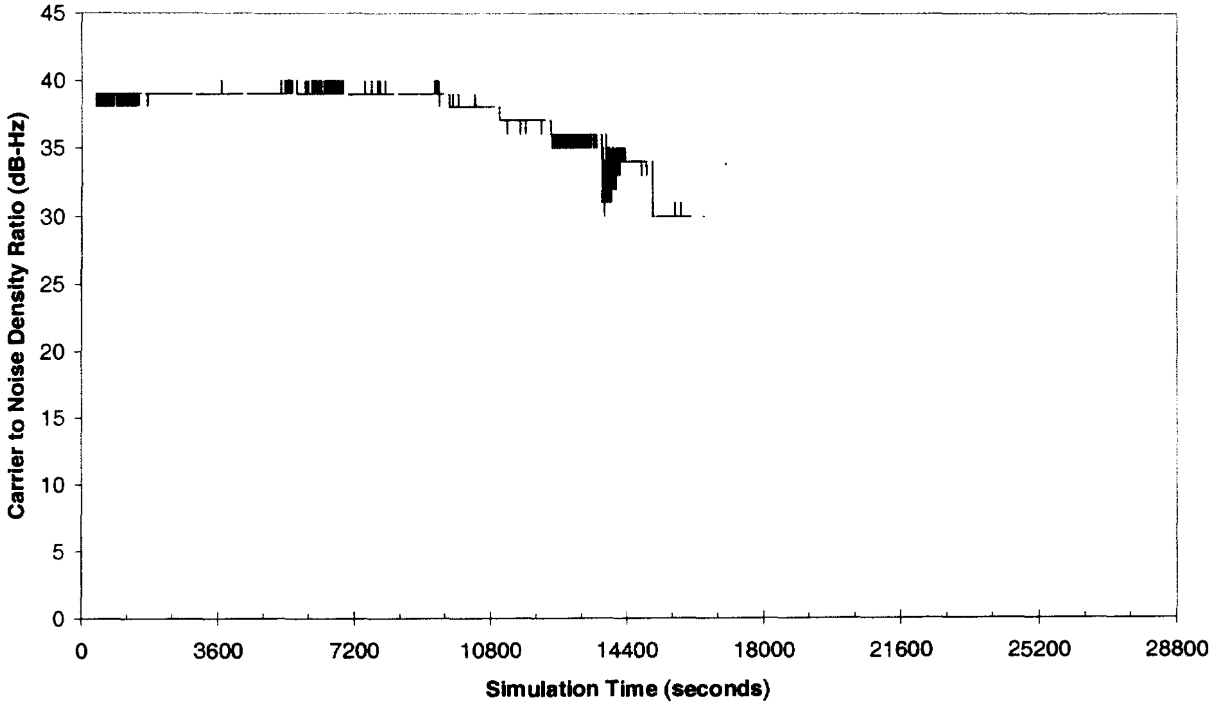

Figure 5-21. Receiver 3 SV 7 C/N$_0$, UWB Mode 7

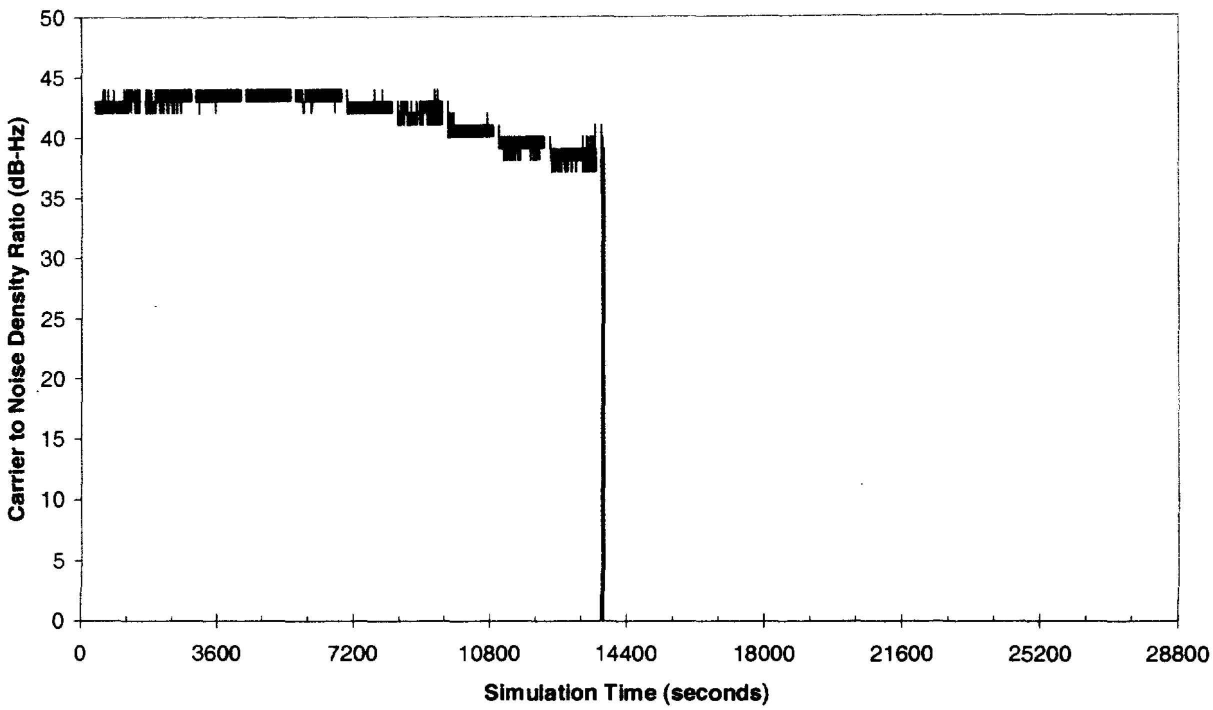

Figure 5-22. Receiver 4 SV 7 C/N$_0$, UWB Mode 7

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